A numerical simulation of $PM_{2.5}$ concentration using the WRF-Chem model during a high air pollution episode in 2019 in Jakarta, Indonesia

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ABSTRACT

Jakarta, as a megapolitan city, is always crowded with thousands of vehicles every day which results in decreased air quality due to combustion emissions and may have a significant impact on human health. Particulate matter ($PM_{2.5}$) is a pollutant that has an aerodynamic diameter of fewer than 2.5 micrometers and is very easy to enter the human respiratory system so it can affect health. In the dry season, rain as the main natural mechanism for reducing $PM_{2.5}$ occurs very rarely, causing an accumulation of $PM_{2.5}$ concentrations in the atmosphere. The weather research and forecasting model coupled with the chemistry (WRF-Chem) model is a dynamic model that works with atmospheric chemistry combined with meteorological variables simultaneously. This study aims to simulate the concentration of $PM_{2.5}$ in Jakarta during the high air pollution episode from 20 to 29 June 2019 with the WRF-Chem model based on the T1-MOZCART chemical scheme. Spatial analysis was conducted to determine the distribution of $PM_{2.5}$ concentrations during high air pollution episodes in Jakarta. Validation of the simulation model was based on three observation sites, one in South Jakarta and two in Central Jakarta. The results showed that the highest correlation is 0.3 and the lowest root mean square error (RMSE) is 26.4, while the simulations still tend to overestimate the $PM_{2.5}$ concentration.

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1. INTRODUCTION

Jakarta is one of the most polluted metropolitan cities in the world with quite poor air quality and high particulate concentrations [1]. Poor air quality is one of the causes of premature death in the world and exposure to fine particles such as particulate matter ($PM_{2.5}$), which is an important element of air pollution in cities, is associated with increased cardiovascular disease and premature death [2]. $PM_{2.5}$ is a mixture of primary components which can consist of a mixture of heavy metals, organic carbon (OC), elemental carbon (EC), and secondary components such as sulfate, nitrate, ammonium, and secondary organic aerosol (SOA) [3].

According to Statistics Indonesia, in addition to being the center of the economy, Jakarta is also a trade center that has a large population and increasing purchasing power, which causes the use of vehicles to

develop very rapidly. In 2019, there were approximately 20 million registered vehicles in Jakarta [4]. This large number of vehicles contributes to the high concentration of $PM_{2.5}$ in Jakarta.

According to Lestari *et al*. [5], land transportation and the industrial sectors account for 46% and 43% of $PM_{2.5}$ emissions in Jakarta with emissions from heavy-duty vehicles still the highest contributor. Jakarta's air quality is typically worse during the dry season than during the rainy season [6]–[9]. The study by Kusumaningtyas *et al*. [7] showed that the maximum concentration of particulate matter occurs from June to September and then decreases from December to February. Based on previous studies, the concentration of particulate matter can also be influenced by meteorological variables such as rainfall, air temperature, and wind speed [10]–[14]. Rainfall can reduce atmospheric particulate pollution, including $PM_{2.5}$ [15]. On days where there has been no rain for a long time, the air that does not fluctuate too much, sunny weather, the presence of an inversion layer of temperature, or wind speeds that are close to calm allow pollutants to remain in the atmosphere of an area and increase in concentration.

The weather research and forecasting model coupled with chemistry (WRF-Chem) is a model that coupled the meteorological model and atmospheric chemistry models [16], [17]. WRF is often used to simulate or forecast meteorological events that influence the variability of the concentration of pollutants in the atmosphere [18]. Meanwhile, the WRF-Chem has been used to simulate atmospheric chemistry based on the atmospheric model so that it can be taken into consideration how the meteorological process influenced the composition of atmospheric chemistry and pollutants [19], [20]. Based on previous research, WRF-Chem has been widely used to estimate the concentration of PM in subtropical regions [21]–[24], but research in tropical regions like Indonesia is still limited and usually related to wildfire cases [25], [26]. Research on air pollution in Indonesia using WRF-Chem in Indonesia is still limited due to the complexity of the precise parameterization for specific areas in Indonesia which have complex atmospheric conditions and there is not enough reference for this, however, this research must be continuously developed. Based on a study by Liu *et al*. [27], the WRF-Chem model may simulate the $PM_{2.5}$ concentration with an overestimated output, but the model error is not significant.

The WRF-Chem uses several parameterization schemes that are selected based on the conditions of an area to be modelled or analysed for simulating air pollutants. The choice of parameterization scheme will affect the model output [28]. In this study, the parameterization that will be used refers to Liu *et al*. [27], to simulate the $PM_{2.5}$ during the 2019 high air pollution episode in Jakarta from 20 to 29 June.

2. RESEARCH METHOD

The research location chosen was the Special Capital District of Jakarta has coordinated 5°19'12"S to 6°23'54"S and 106°22'42"E to 106°58'18"E with an area of 740.3 km^2. Jakarta is often suffered from a low air quality problem with vehicle emissions being a major factor in declining air quality in Jakarta. We used $PM_{2.5}$ concentration datasets from two monitoring stations in Central Jakarta and one station in South Jakarta owned by BMKG and US-AirNow which locations as shown in Figure 1.

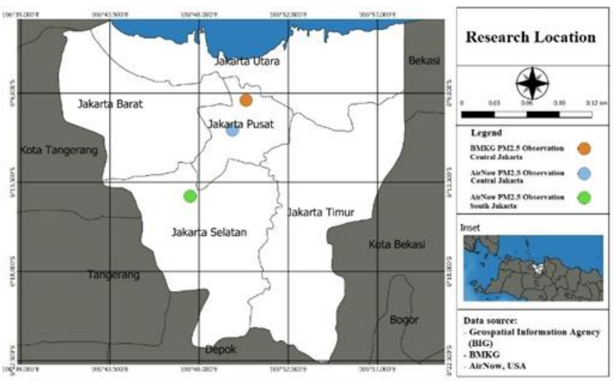


Figure 1. Research and $PM_{2.5}$ monitoring sites locations

WRF-Chem is a WRF software used on the Ubuntu (Linux) platform which is juxtaposed with the chemistry (Chem) model and was developed by National Oceanic and Atmospheric Administration (NOAA) or Earth System Research Laboratory (ESRL). WRF-Chem can simulate the emission transport, mixing, and chemical formation of trace gases and aerosols simultaneously using climatological data [19]. The chemical

parts of WRF-Chem treat transport processes (progressive, convective, and diffusion), wet and dry deposition, chemical transformation, emissions, photolysis, aerosol chemistry, and dynamics (including inorganic and organic aerosols) [29]. We used the global forecast system (GFS) dataset as input for meteorological parameters.

WRF-Chem is a model of air pollution that combines meteorological factors and atmospheric chemistry together (online coupled). Each region has a characteristic and unique atmosphere that cannot be compared to other regions, the parameterization scheme in WRF-Chem is expected to be able to mathematically simulate the uniqueness of the region by choosing the right parameterization. With a process that is too small or physically complex, parameterization is used to obtain a more accurate prediction result which is represented in a simpler model [30]. This study used 3 domains in the WRF-Chem process the 3rd domain covers Special Capital Region of Jakarta (DKI Jakarta) as shown in Figure 2.

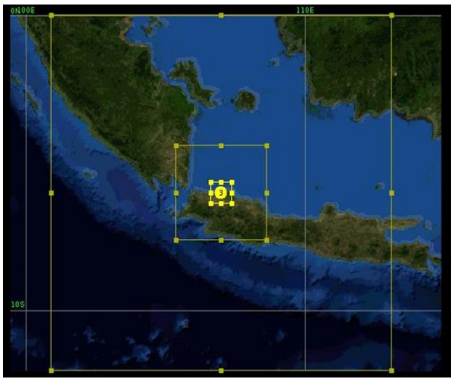


Figure 2. Domains used in running the WRF-Chem process

Parameterization is used as a representation of small-scale weather processes affecting larger scales. The parameterization of weather modelling consists of microphysics, cumulus or convection, surface land model, planetary boundary layer (PBL), atmospheric radiation, and physical interactions. In a study by Chen *et al*. [31], a combination of Yonsei University (YSU) PBL, Goddard SW, and geophysical fluid dynamics laboratory (GFDL) LW schemes showed the greatest consistency between simulated and observed $PM_{2.5}$ values. Although the PBL scheme has a dominant impact on the simulation of meteorological variables, the selection of the LW and SW schemes is equally important. In other research, Lin Microphysics, Grell 3D Cumulus, Mellor-Yamada-Janjic (MYJ) PBL, rapid radiative transfer model (RRTMG LWR), and RRTMKG SWR were used in the parameterization that simulated PM concentration in Jakarta [28]. In this study, we used the WRF-Chem configuration as in Table 1.

Table 1. WRF-Chem configuration

Domain	
Domain d03	Latitude: -6,44733 to -5,9886º, longitude: 106,604 to 107,066º, 3 km^2 spatial resolution
Vertical levels	Number of levels: 38σ levels, model top: 10hPa
Physics	
Microphysics	Morrison, Thompson and Tatarskii (option 10)
Longwave radiation	RRTMG (option 4)
Shortwave radiation	RRTMG (option 4)
PBL physics	Bougeault and Lacarrere (option 8)
Surface layer	Revised Monin-Obukhov scheme (option 1)
Cumulus	New Grell (option 5)
Land–surface	Noah land – surface model (option 2)
Urban Surface	Multi-layer, Building Environment Model (BEM) scheme
Chemistry	
Chemistry option	T1-MOZCART (option = 114)
Photolysis option	Madronich F-TUV photolysis
Biogenic emmision	MEGAN biogenic emissions online based upon the weather, land use data (option = 3)
Anthropogenic emissions	MOZCART (MOZART + GOCART aerosols) emissions
GOCART dust emissions included	Include GOCART dust emissions with AFWA modifications (option = 3)
Input data	
Land use	USGS
Albedo	NCEP
Boundary conditions Chemistry	MOZART–4 (global CTM)
Atmospheric dataset	NCEP GDAS/FNL 0.25 Degree Global Tropospheric Analyses and Forecast Grids

T1-MOZCART presents an update to the MOZART-4 chemical gas phase mechanism in the chemical option (chem_opt) option in the WRF-Chem scheme. T1-MOZCART has 142 gas-phase species compared to 81 gas-phase species in MOZCART. In addition, there is an increased understanding of the volatile organic compound (VOC) oxidation process through laboratory measurements, as well as the need to better represent secondary organic aerosol precursors. Recent field measurements of increasing amounts of isoprene oxidation products, as well as individual aromatic hydrocarbons and terpenes, allow a more precise evaluation of the model [32]. We used the Pearson correlation coefficient and root means square error (RMSE) in modelling validation.

3. RESULTS AND DISCUSSION

Figure 3 illustrates a comparison of surface temperature observations from the meteorological station of Kemayoran, Central Jakarta (BMKG headquarter), and the simulation of WRF-Chem using the parameterization in Table 1 during high air pollution episode in Jakarta. The diurnal variations in surface temperature can be simulated well as shown by the correlation coefficient of 0.96 and RMSE of 2.6 which is not much different from the standard deviation of the observational data which is 2.2. Simulation of the surface temperature performs better results in simulating temperature from morning to noon and is less accurate in the late afternoon to night time.

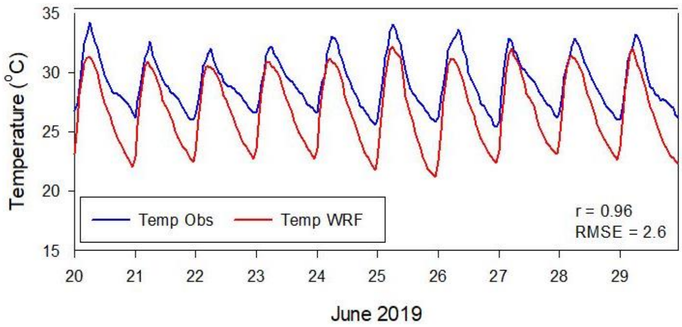


Figure 3. Comparison of hourly surface temperature between observation and WRF-Chem simulation on 20 to 29 June 2019 at Central Jakarta

The simulation of surface wind speed at the BMKG headquarter, Central Jakarta also shows better results in the morning to noon and performs poor results in the afternoon to early morning as shown in Figure 4. In general, surface wind speeds during periods of high air pollution episodes in Jakarta can be simulated well by WRF-Chem which is indicated by a correlation coefficient of 0.76 and an RMSE of 1.8 which is still smaller than the standard deviation of surface wind observations of 2.8.

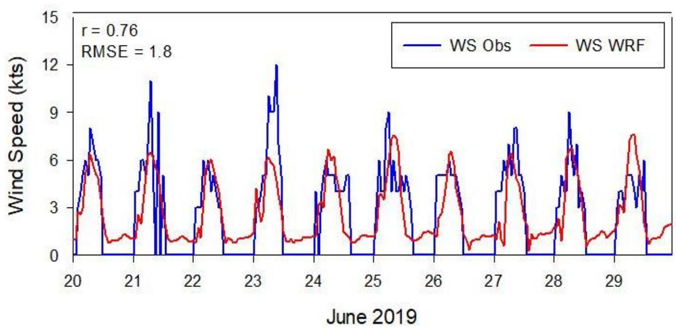


Figure 4. Comparison of hourly wind speed between observation and WRF-Chem simulation on 20 to 29 June 2019 at Central Jakarta

Figure 5 is a spatial distribution of the $PM_{2.5}$ concentration from 20 to 23 June 2019 at 8.00 am local time (LT) in Jakarta simulated by the WRF-Chem model. The samples were chosen at 8.00 am because those times coincided with the start of office hours, when in fact many vehicles were congesting the streets in Jakarta. $PM_{2.5}$ concentration shows an increase starting on June 22, 2019, with an average concentration above 65 µg/m^3 with a higher concentration in the eastern part of Jakarta. Then the next day at 8.00 am the average concentration in Jakarta exceeded 95 µg/m^3 almost covering the entire area of Jakarta.

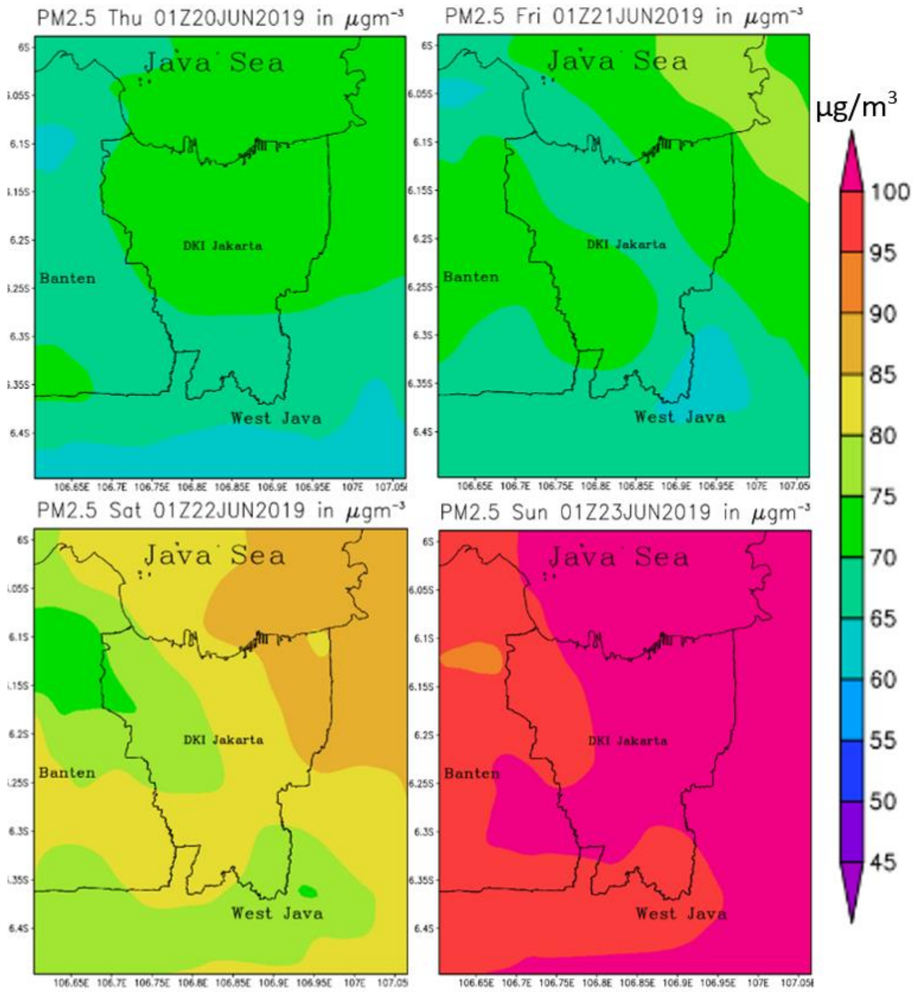


Figure 5. Spatial variability of $PM_{2.5}$ concentrations during high air pollution episode from 20 to 23 June 2019 at 8.00 am LT in Jakarta simulated by the WRF-Chem

Figure 6 shows the spatial distribution of $PM_{2.5}$ concentrations from 24 to 29 June 2019 at 8.00 am LT in Jakarta. The simulation model shows that 24 and 27 June 2019 had the highest concentration throughout the study period with an average concentration exceeding µg/m^3. Then, the $PM_{2.5}$ concentration decreased on 29 June 2019 with an average of 70 µg/m^3. In general, the spatial distribution of $PM_{2.5}$ concentrations in Figures 5 and 6 shows that the model simulates a higher $PM_{2.5}$ concentration in the eastern and northern parts of Jakarta.

Based on Figure 7, is a graph of hourly $PM_{2.5}$ concentrations averaged in all observation sites and an average of the hourly concentration from the simulation with T1-MOZCART. The observation shows an increase of $PM_{2.5}$ during the late afternoon before evening, this high concentration state will last until 8 am LT. After 8 am LT is the time the $PM_{2.5}$ concentration starts to decrease until 5 pm. The higher $PM_{2.5}$ concentration observed at night-time to early morning compared to daytime is due to changes in the boundary layer height at night-time due to the cooling of the near-surface atmosphere so that $PM_{2.5}$ will be concentrated near the surface [31]. The hourly $PM_{2.5}$ simulation follows the observation well on average from 1 am to 4 pm LT, although it is higher than the observed value.

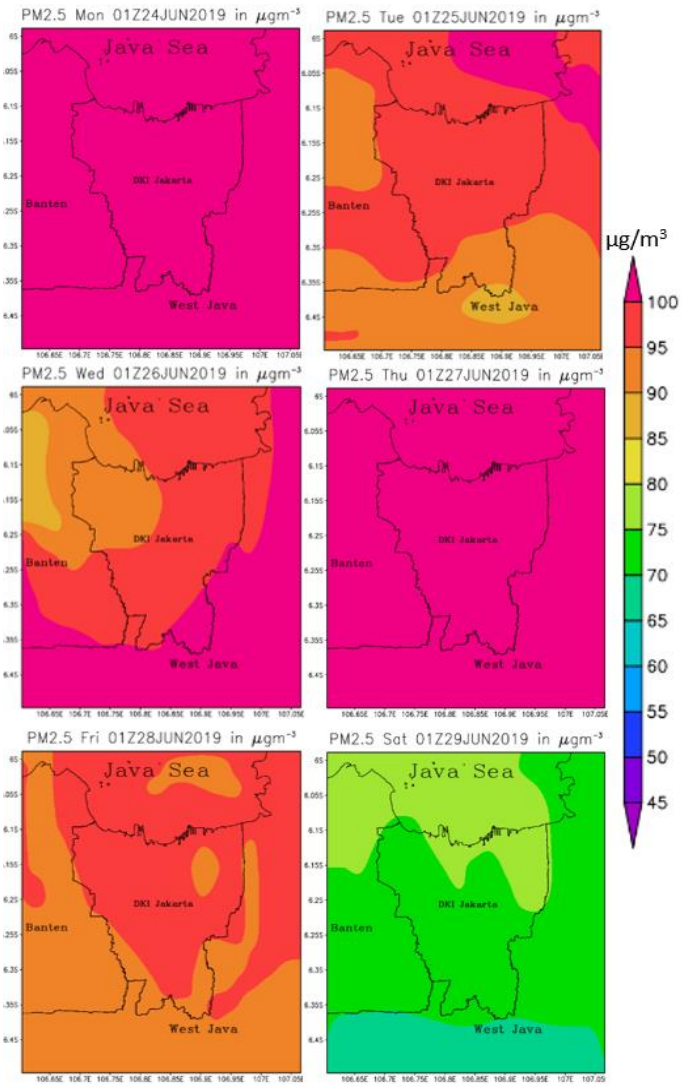


Figure 6. Spatial variability of $PM_{2.5}$ concentrations during high air pollution episode (24 to 29 June 2019) at 8.00 am LT in Jakarta simulated by the WRF-Chem

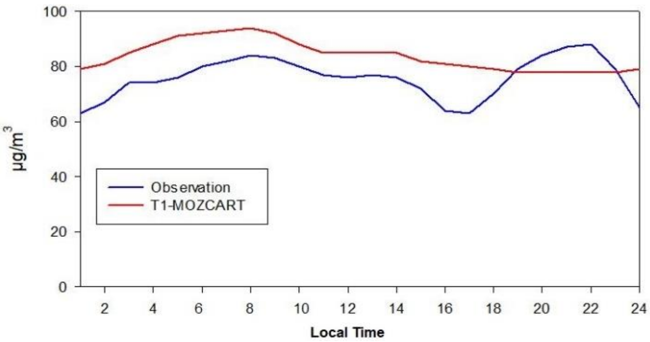
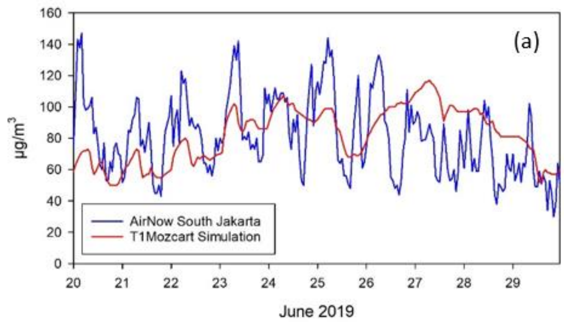


Figure 7. Hourly average $PM_{2.5}$ concentrations in all observation sites and an average of the simulations

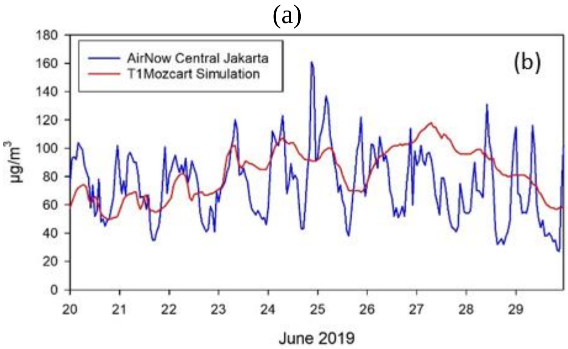
Figure 8 shows the comparison of $PM_{2.5}$ concentrations from the model output and observations from three observation sites in Jakarta. Both of the AirNow observation sites at South and Central Jakarta and AirNow South Jakarta from 20 to 29 June 2019 show average concentrations above 65 μg/m^3 which is the

daily threshold for $PM_{2.5}$. Based on Figure 8(a), the simulation tends to underestimate the $PM_{2.5}$ concentration from 20 to 26 June 2019, while generating an overestimated concentration on average from 26 to 29 June 2019. The simulation generated by T1-MOZCART at the AirNow observation site in South Jakarta can depict a decreasing trend in $PM_{2.5}$ concentration after 27 June 2019.

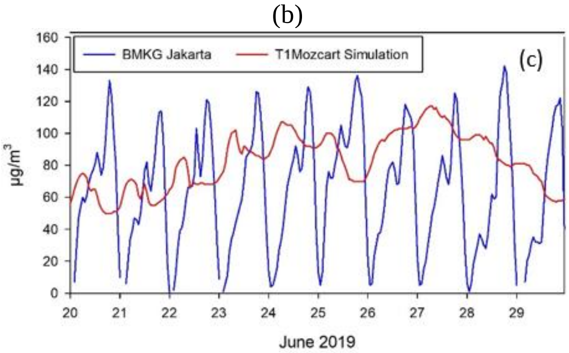
The $PM_{2.5}$ concentration simulation in Central Jakarta at the AirNow observation site shows a slightly overestimated result except on 20, 21, 25, and 26 June 2019 as shown in Figure 8(b). The simulation can simulate up to 120 µg/m^3 with a minimum value that is still above the observation. The peak period of the highest $PM_{2.5}$ concentration according to observations occurred on 25 June while the model shows on 27 June, but the decline after 27 June can be well simulated. Figure 8(c) shows a graph of the simulated and observed $PM_{2.5}$ concentrations with a three-hour resolution at the BMKG headquarter in Central Jakarta whose observation data also has a three-hour resolution. Similar to the observations at the other two sites, observed $PM_{2.5}$ concentrations at the BMKG headquarter in Central Jakarta have also experienced a decline in trend since June 27, which the decline can be simulated by the model although with lower variability and tends to be closer to the average. Furthermore, the highest concentration at the observation site at the BMKG headquarter occurred on June 25, while in the model it occurred on June 27. Some data are blank and data that are too low at the observation site at the BMKG headquarter occurs due to daily periodic maintenance from midnight to morning on the equipment used. We evaluated the $PM_{2.5}$ simulation based on observation datasets from three observation sites in Jakarta using three parameters, i.e. correlation coefficient (r), RMSE, and Bias as in Table 2.



(a)



(b)



(c)

Figure 8. Comparison of $PM_{2.5}$ concentrations from the WRF-Chem model and the observations at (a) AirNow South Jakarta, (b) AirNow Central Jakarta, and (c) BMKG headquarter Jakarta

Table 2. Validation of the $PM_{2.5}$ simulation using the T1-MOZCART scheme at three observation sites in Jakarta

	AirNow South Jakarta	AirNow Central Jakarta	BMKG HQ Central Jakarta
r	0.27	0.3	-0.24
RMSE	26.4	26.7	48.5
Bias	0.7	8.1	19.9

Although the correlation coefficients were low, the highest $PM_{2.5}$ concentration correlation with the observational data is shown in the simulation at the AirNow observation site in Central Jakarta, while the lowest is shown in the simulation at the BMKG headquarters in Central Jakarta. RMSE at the two AirNow observation sites is not much different and better than at BMKG headquarters. Meanwhile, the smallest bias is shown by the $PM_{2.5}$ simulation at the AirNow observation site in South Jakarta, while the simulations at two other observation sites are quite overestimated the observation. This overestimate $PM_{2.5}$ simulations might come from the WRF-Chem parameterization schemes used in this research, that also based on a study by Liu *et al.* [27].

4. CONCLUSION

We analyzed the spatial distribution of the output of the $PM_{2.5}$ concentration simulation using T1-MOZCART scheme in Jakarta during a high air pollution episode from 20 to 29 June 2019. The WRF simulation performs better in simulating surface wind speeds but tends to underestimate the surface temperature. Meanwhile, a simulation of $PM_{2.5}$ concentration shows that during the peak of the high pollution episode, the average $PM_{2.5}$ concentrations are more than 100 $\mu g/m^3$ at 08.00 am. The lowest $PM_{2.5}$ concentration at 08.00 pm is in the southern and western parts of Jakarta. A look at how the simulation changes over time showed that it tends to get higher at night and get lower afternoon. We validated the simulation of $PM_{2.5}$ concentration using T1-MOZCART scheme based on observation data and found that the simulation shows better performance in correlation, RMSE, and bias at two AirNow observation sites than at BMKG headquarters. Overall, the simulation shows an overestimate at all three observation sites.

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